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Sustainable energy development strategies in the rural Thailand: The case of the improved cooking stove and the small biogas digester

Bundit Limmeechokchai[a,*], Saichit Chawana[b]

[a]*Sirindhorn International Institute of Technology, Thammasat University, P.O. Box 22 Thammasat Rangsit Post Office, Pathumthani 12121, Thailand*

[b]*The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand*

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Abstract

This paper presents the strategies to overcome barriers to the adoption of improved cooking stove (ICS) and small biogas digester (SBD) technologies in Thailand. Firstly, to obtain the appropriate strategies to implement the ICS and the SBD, a pattern of energy consumption in the residential sector is investigated. Then the potential of reduction of energy consumption and corresponding emissions by the ICS and the SBD is assessed. The identification and ranking of barriers to the adoption of the ICS and the SBD technologies are also investigated. In this study the Long-range Energy Alternatives Planning System (LEAP) model is used to assess the energy consumption and the corresponding emissions reduction. Then, the Analytic Hierarchy Process (AHP) model is used to identify and rank the barriers. Results from the LEAP model show that the cumulative total energy consumption and corresponding emissions reductions during the period 2002–2030 by the ICS are 27,887.7 ktoe and 10,041.0 thousand tonnes of CO_2 equivalent, respectively. An average emissions reduction cost per tonne of CO_2 equivalent per year is US$ 0.95 for a fuel wood cooking stove and US$ 0.35 for a charcoal cooking stove. Regarding the SBD, the cumulative total liquefied petroleum gas (LPG) consumption reduction and CO_2 mitigation are 5780.9 ktoe and 1548.8 thousand tonnes of CO_2 equivalent during the period 2002–2030, respectively. Results from AHP analysis of ranking of barriers show that the three most important barriers in the adoption of the ICS are (i) high investment cost, (ii) lack of information, and (iii) lack of financial sources. For the SBD, the three most important barriers are (i) high investment cost, (ii) lack of financial sources, and (iii) lack of

*Corresponding author. Tel.: +662 986 0009; fax: +662 986 9112.
E-mail address: bundit@siit.tu.ac.th (B. Limmeechokchai).

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experts and skilled manpower. The sustainable energy triangle strategy (SETS) is implemented to overcome barriers in the adoption of the ICS. Results show that the traditional cooking stoves are successfully replaced (more than 20% per year). Regarding the SBD, the biogas pool project (BPP) is implemented to resolve the over supply of biogas. Results also show that the BPP is a proper strategy.

Keywords: Improved cooking stove; Traditional cooking stove; Biogas digester; The residential sector; CO_2 emissions; Ranking of barriers; Sustainable energy triangle strategy; Biogas pool project

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1. Introduction

Nowadays, the ICS and the SBD are popular renewable energy technologies (RETs) to reduce energy consumption and corresponding emissions in developing countries. In Thailand both strategies have been studied and implemented for more than 20 years [1].

However, the ICS implementation failed. In 1996 only 26 units of the ICS were used [1], accounting for 0.63% of total stove usage in the residential sector. Total potential of the ICS production in 2001 was 8097 units [2]. In addition, the traditional cooking stove (TCS) usage in 2001 was around 4.9 million units [1]. Consequently, the share of the use of the ICS in 2001 was around 0.17% of the total stove usage in the residential sector. The ICS has been implemented to reduce energy consumption and emissions, the lesson from the failure of ICS implementation in Thailand is learnt and the strategy to overcome the barriers is proposed.

Regarding the SBD, at present the biogas digester is a popular project for livestock farms to invest in as a waste treatment system. The target of SBD construction in 2001 was 60,000 m^3 [3]. The report showed that 60,120 m^3 of the SBDs were constructed in 2001 and many digesters were not constructed because of the limitation of the project budget. In this study the SBD means the biogas digester with the size ranging from 12 to 100 m^3 [4]. Biogas is used to substitute the use of any form of fuels such as fuel wood, charcoal, and LPG for cooking and electricity generation. However, biogas production from the SBD in Thailand is not enough to generate electricity. Most biogas produced from the SBD is used for cooking in households. Therefore, it is assumed in this study that biogas is used in place of LPG only. At present the problem of the SBD is the oversupply of biogas. Though the oversupply of biogas occurs in some farms, it seems to have severe consequences because the farmers release biogas to the atmosphere. It is very dangerous to the global climate because the main composition of biogas is methane. Therefore, the strategy to solve this problem is needed. Finally, the proper strategy to overcome the problems of the oversupply of biogas is presented.

2. Methodology

To succeed in the adoption of the ICS and the SBD technologies, the strategies to the implementation of both technologies are proposed. However, to obtain the appropriate strategy to overcome the barriers and the problems in the adoption of the ICS and the SBD technologies, the current situation of the energy consumption in the residential sector is investigated first. Then the barriers and the problems in the adoption of the ICS and the SBD technologies are identified. As a result, the energy consumption in the base case, hereafter call ‘BAU scenario’, is investigated through the LEAP model. Then the ICS and the SBD strategies are introduced as the option to reduce energy consumption and corresponding emissions. In this study, only methane (CH_4) which is emitted from cooking stove is considered. There are no emissions from the use of electricity appliances because the emissions are already considered as the emissions from power plant. The emissions are presented in terms of CO_2 equivalent when global warming potential (GWP) of CH_4 of 21:1 is considered [5]. This study provides a quantitative comparison of long-term energy ‘scenarios’ for rural Thailand. The study period starts in 2002 and ends in 2030. The base year is 2002. Both primary and secondary data are used. They are available from field surveys, Thai government agencies, and private agencies. The study compares the impacts of the ICS and the SBD scenarios on providing energy services with the BAU scenario. The results from the comparison are the indication of the change that will need to be made to change the use of energy toward environmental sustainability. As mentioned above, the LEAP model is used to obtain the potential of the energy consumption and corresponding emission reductions. Therefore, the assessment of the energy consumption

and corresponding emission reductions is based on the available data of the LEAP model. On the other hand, the AHP model is used to identify and rank the barriers to the adoption of the ICS and the SBD. Details of the LEAP model and the AHP model are as follows.

2.1. Long-range energy alternatives planning system (LEAP) model

The LEAP model has been developed by the Stockholm Environment Institute (SEI), Boston centre and used to evaluate energy development policies [6]. The concept of LEAP is an end-use driven scenario analysis. Additionally, the model includes the technology and environmental database (TED) to estimate environmental emissions of the energy utilization. The LEAP model framework is disaggregated in a hierarchical tree structure of four levels: sector, sub-sector, end-use, and device [6] (see Fig. 1). The model contains two main modules: energy demand module and TED module. In the energy demand module, the energy intensity values along with the type of fuel used in each device are required to estimate the energy requirements at sector, sub-sector, and end-use level. The emission factors of different pollutants in the TED module are linked to the device level to appraise the environmental emission from the energy utilization during the planning horizon. The model requires data for at least the base year and any of the future years. Then, the future energy demand and emissions are estimated for the other years by interpolation, extrapolation or the growth rate methods. In this study, the current energy situation is created in the starting year and the BAU scenario can be developed assuming a contribution of current trends. Then, the ICS and the SBD scenarios are developed as alternative cases. The LEAP model emphasizes the detailed evaluation of specific energy problems within the context of integrated energy and environmental planning for each scenario. Fig. 1 also shows input data in tree structure for Thailand in the energy demand module in the LEAP model. Only input data in the greater Bangkok area are shown as an example because input data in the other areas are assumed to be the same as in greater Bangkok. The difference is the penetration rates of devices.

2.2. Analytic hierarchy process (AHP) model

The AHP model has been used for prioritizing alternatives associated with target objectives of the project. It is known as a pair-wise comparison method and a popular method in evaluation of problems. It is a technique used for setting priority in a complex, un-anticipated, multi-criteria problematic situation. It is used to solve complex decision-making problems in different areas such as planning, measuring performance, and choosing the best policy after finding a set of alternatives [7]. In this study a practical AHP model is developed for the prioritization of stakeholders, criteria, and barriers in the adoption of the ICS and the SBD technologies. The model has four level structures. The first level is the objective of the decision while the second is the groups of stakeholder who have perception of the barriers. The third level is the criteria and the fourth level is the barriers (see Fig. 2).

2.2.1. Description of stakeholders, criteria, and barriers

1. The energy and environmental experts are the people who consult the policy makers to adopt the appropriate policy and the people who encourage, give information on the benefits of such technologies, and suggest to the users how to use the technology.

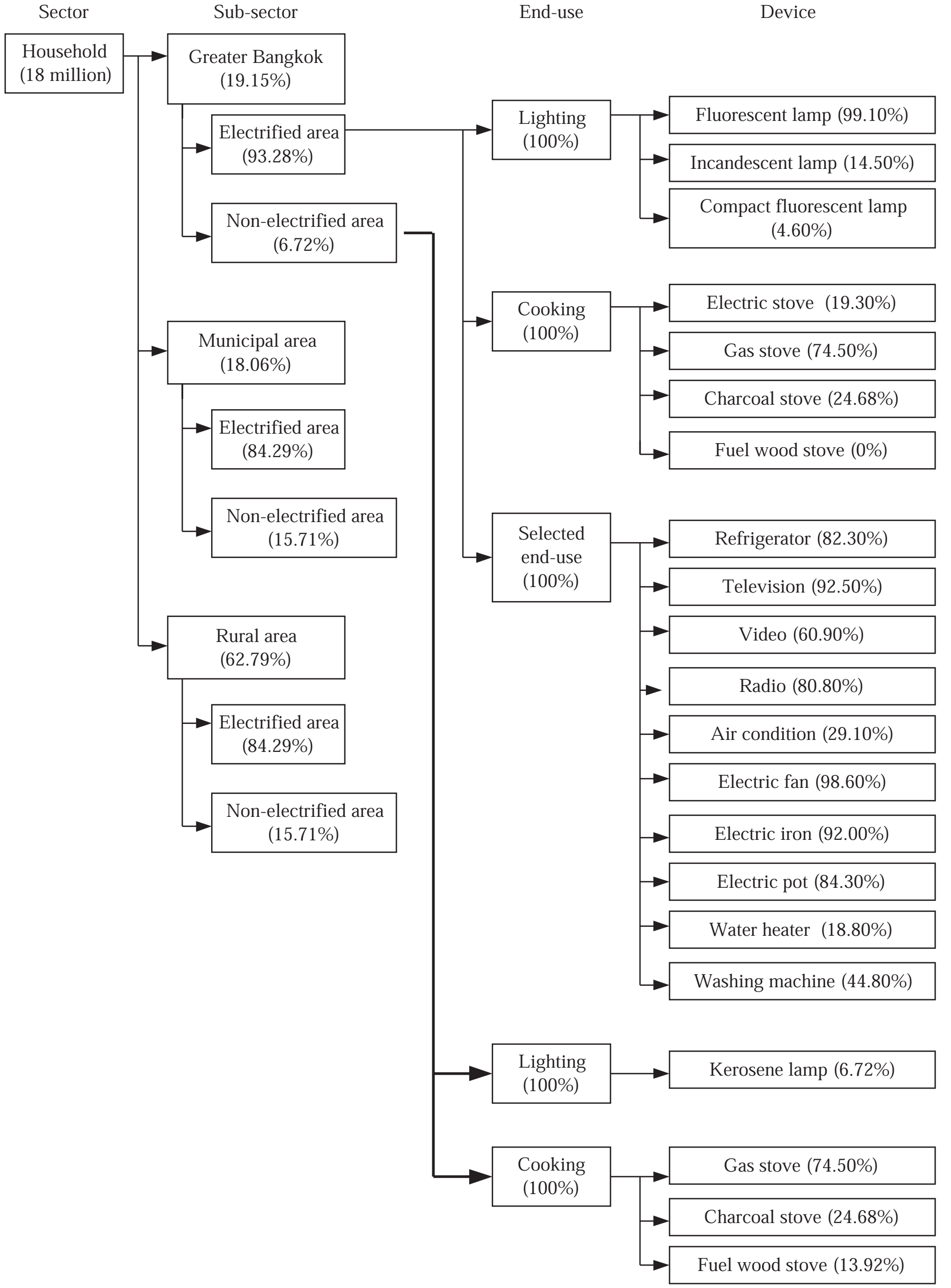

Fig. 1. Tree structure in the energy demand module for Thailand in the LEAP model.

2. Lack of finances means that the investors cannot access financial sources. Most RET investors are individuals and have limited personal records of accounts and assets that are required by financial institutes to show that the investors are creditworthy.

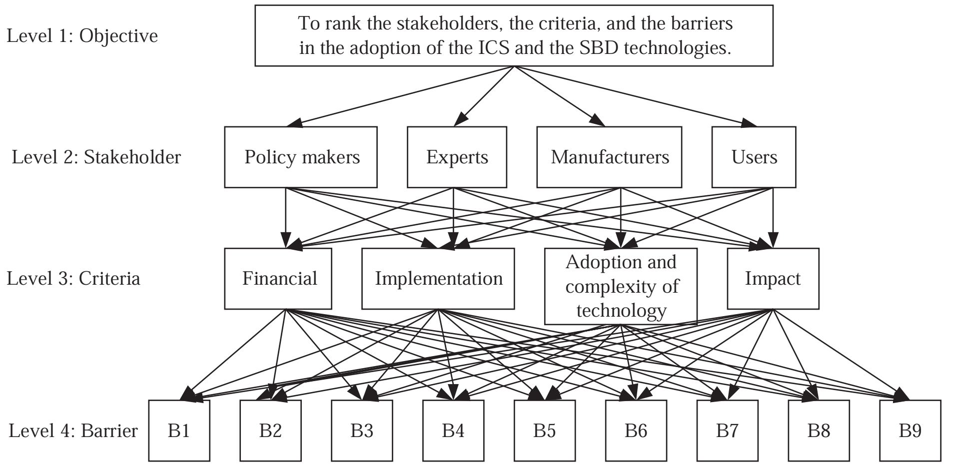

Fig. 2. The structure of the AHP model of the study.

3. Lack of information prevents the related people on RETs from being clear about the benefits of the RETs. For example, in order to adopt the SBD, the benefits from the biogas digester technology must be clear. The benefit of the SBD is money saving on electricity and LPG expenditures by using biogas instead.
4. Lack of experts and skilled manpower means an absence of indigenous capability. A basic level of indigenous technological capability is essential to facilitate the process of sustainable RETs. Lack of experts and technically trained staff to install, operate and maintain RETs is often a problem.
5. Multiplicity of authorities and lack of co-ordination between authorities means that the responsibility for the RETs is divided among several government departments and the co-ordination among them is often poor. The multiplicity of authorities of RETs causes a lack of commitment to push forward the revised policy and planning regulations needed to aid adoption of RETs.

3. The energy consumption and corresponding emissions in the BAU scenario

3.1. Input data and assumptions

Input data for the LEAP model are (i) number of households, (ii) end-use device's penetration rate, and (iii) energy intensity for each end-use device. The number of households is calculated based on data from the Department of Provincial Administration, Ministry of Interior (DoPA) [8] and the National Economic and Social Development Board (NESBD) [9]. Regarding the end-use device's penetration rate, data from the National Statistical Office (NSO) [10] are used to create the econometric model for projection of the penetration rate of each end-use device in the period 2003–2030. End-use devices considered in this study are separated into three groups: lighting, cooking, and selected end-use devices. Lighting devices include fluorescent lamps, incandescent lamps, and compact fluorescent lamps (CLF). Cooking devices include electric stoves, gas stoves,

Table 1
Energy consumption and Emission in the BAU scenario in the selected years

Item	2002	2005	2010	2015	2020	2025	2030
-Energy consumption (ktoe)	7952.3	8786.7	10,263.6	12,135.5	13,900.9	15,455.4	16,290.6
-Emission (million tonne of CO_2 equivalent)	2.2	2.3	2.4	2.4	2.4	2.5	2.5

charcoal stoves, and fuel wood stoves. Selected devices include refrigerators, televisions, video players, radios, air conditioners, electric fans, electric irons, electric pots, water heaters, and washing machines. In addition, the energy intensities for all end-use devices, except gas stoves, charcoal stoves, and wood stoves, are calculated by using Eq. (1). Regarding the gas stoves, charcoal stoves, and wood stoves, the energy intensity is calculated by using Eq. (2).

$$I_i = H_i \times C_i \times N_i \tag{1}$$

where I_i = Energy intensity for end-use device type i (kW h/year/HH), H_i = the usage hour per year of end-use device type i (h/year), C_i = Average capacity of end-use device type i (kW), N_i = Average number of end-use device type i per household (unit/HH), i = Type of end-use device, and HH = Household.

$$I_j = F_j \times C_j \times N_j \tag{2}$$

where I_j = Energy intensity for stove type j (kg/stove/year), F_j = the usage time per year of stove type j (time/year), C_j = Average energy consumption per batch of stove type j (kg/batch), N_j = Average number of stoves type j per household (unit/HH), and j = Stove type.

3.2. Results of the BAU scenario from the LEAP model

The energy consumption and the corresponding emissions for the BAU scenario in the residential sector are obtained from the LEAP model as shown in Table 1. The final energy consumption increases from 7952.3 thousand tonnes of oil equivalent (ktoe) in the base year to 16290.6 ktoe in 2030. The emission increases from 2.2 million tonnes of CO_2 equivalent in the base year to 2.5 million tonnes of CO_2 equivalent in 2030. The emission in 2030 is not so high compared to the base year due to replacement of TCS by ICS as planned by government.

4. The potential of the reduction of the energy consumption and the corresponding emission through the improved cooking stove (ICS)

4.1. Input data and assumption

In the ICS scenario, it is assumed on the basis of the present policy on the ICS implementation of the Thai government [11], that the traditional charcoal cooking stove is expected to be completely replaced by the improved charcoal cooking stove before 2011 in the greater Bangkok and the municipal areas. Based on the existing trend, the traditional

charcoal cooking stove will be completely replaced in 2020 in the rural area. The target can be achieved by the sustainable energy triangle strategy (SETS) instead of the present strategy in the ICS scenario. Unlike the charcoal cooking stove, the government has not paid much attention to the fuel wood cooking stove. Based on the penetration rates of the improved charcoal cooking stove, the penetration rates of the improved fuel wood cooking stove for the ICS scenario are 10% in 2005, 50% in 2010, and 100% in 2015 for the outer greater Bangkok and the municipal areas. For the case of the rural area, the penetration rates are 10% in 2005, 30% in 2010, 60% in 2015, 90% in 2020, and 100% in 2023. These penetration rates are then input into the LEAP model under the ICS scenario. Consequently, the energy consumption and the emissions by the ICS scenario are obtained.

Not only are the potential reductions of the energy consumption and the emissions assessed, but also the benefit/cost ratio analysis as well. To analyze the benefit/cost ratio of the ICS, the benefits concerned in this study include fuel saving and cost saving. Fuel saving is calculated based on the difference of energy consumption per year between the traditional cooking stove (TCS) and the ICS. The cost saving is obtained from the difference between the life span of the TCS and the ICS. The life span of the TCS is a half-year and two years for the ICS [12]. Thus, during two years the users spend money for the ICS only one time, while they have to spend the money for the TCS four times. In 2001 the stove price for the TCS was US$ 1.88 per stove and US$ 3.75 per stove for the ICS [12]. As a result, the cost saving is US$ 1.89 per stove per year. The emission reduction cost is obtained by dividing the incremental investment cost of the ICS (stove price) by the emission reduction. Though the benefits and the costs of the ICS are obtained, this information is not sufficient for the users or the investors to make a decision on the ICS investment. Thus, the benefit/cost ratio (B/C ratio) of the ICS is assessed as a criterion for decision making. In addition, the sensitivity analysis is applied to validate the results. Since stove efficiency may increase during the implementation period due to research and development, considered parameters in the sensitivity analysis are the change of the ICS price and the ICS efficiency. Therefore, in sensitivity analysis, it is assumed that the price per unit of the ICS increases by 25% and 50%, and decreases by 25% and 50%. At present, existing efficiencies of the ICS are 29% for the fuel wood cooking stove and 32% for the charcoal cooking stove whereas the efficiency of the TCS is 21% for both the wood cooking stove and the charcoal cooking stove [2,13]. Based on the efficiencies of the existing stove, it is assumed that the ICS efficiency increases from 29% to 35% for fuel wood cooking stoves and increases from 32% to 40% for charcoal cooking stoves. As a result, ten scenarios are performed as shown in Table 2.

4.2. *Results of the ICS scenario from the LEAP model*

Results clearly show that the energy consumption in the residential sector is reduced by 136.7 ktoe in 2005 and 1497.0 ktoe in 2030 by the ICS promotion (see Table 3). The average rate of decrease is 34.3% per year. The cumulative total energy consumption reduction during the study period is 27,887.7 ktoe. Corresponding emission is decreased by 0.05 million tonnes of CO_2 equivalent in 2005 and 0.57 million tonnes of CO_2 equivalent in 2030 (see Table 4). The cumulative total corresponding emissions reduction during the study period by the ICS strategy is 10,041.0 thousand tonnes of CO_2 equivalent.

Table 2
Scenarios for the sensitivity analysis on unit price and efficiency of the ICS

Scenario	Fuel wood cooking stove	Charcoal cooking stove
BAU	Stove price: US$ 3.75/unit, Efficiency: 21%	Stove price: US$ 3.75/unit, Efficiency: 21%
2	Stove price: US$ 4.69/unit, Efficiency: 29%	Stove price: US$ 4.69/unit, Efficiency: 32%
3	Stove price: US$ 5.63/unit, Efficiency: 29%	Stove price: US$ 5.63/unit, Efficiency 32%
4	Stove price: US$ 2.81/unit, Efficiency: 29%	Stove price: US$ 2.81/unit, Efficiency: 32%
5	Stove price: US$ 1.88/unit, Efficiency: 29%	Stove price: US$ 1.88/unit, Efficiency: 32%
6	Stove price: US$ 3.75/unit, Efficiency: 35%	Stove price: US$ 3.75/unit, Efficiency: 40%
7	Stove price: US$ 4.69/unit, Efficiency: 35%	Stove price: US$ 4.69/unit, Efficiency: 40%
8	Stove price: US$ 5.63/unit, Efficiency: 35%	Stove price: US$ 5.63/unit, Efficiency: 40%
9	Stove price: US$ 2.81/unit, Efficiency: 35%	Stove price: US$ 2.81/unit, Efficiency: 40%
10	Stove price: US$ 1.88/unit, Efficiency: 35%	Stove price: US$ 1.88/unit, Efficiency: 40%

Table 3
The reduction potential of energy consumption in the residential sector by the ICS strategy

Scenario	Energy consumption reduction potential in the selected years (ktoe)						
	2002	2005	2010	2015	2020	2025	2030
Energy consumption							
BAU scenario	7952.3	8786.7	10,263.6	12,135.5	13,900.9	15,455.4	16,290.6
ICS scenario	7952.3	8650.0	9686.7	11,094.7	12,464.2	13,943.2	14,793.2
Energy reduction	-	136.7	576.9	1040.8	1436.6	1512.3	1497.0

Table 4
The emission reduction potential in the residential sector

Scenario	The emissions reduction potential in selected years (million tonne of CO_2 equivalent)						
	2002	2005	2010	2015	2020	2025	2030
Emission							
BAU scenario	2.22	2.33	2.41	2.44	2.44	2.45	2.47
ICS scenario	2.22	2.28	2.21	2.08	1.92	1.92	1.90
Emission reduction	–	0.05	0.2	0.36	0.52	0.53	0.57

4.3. Results of the benefit-cost analysis of the ICS investment

One unit of fuel wood cooking stove emits 1.98 tonnes of CO_2 equivalent per year with an average emission reduction cost of US$ 0.95 per tonne. Concerning the charcoal stove, the emission is produced 5.43 tonnes of CO_2 equivalent per year with the average emission reduction cost of US$ 0.35 per tonne (see Table 5).

The B/C ratio is 3.87 for the fuel wood cooking stove and 17.58 for the charcoal cooking stove. Even if the ICS price increases by 50% the B/C ratio of the ICS is still higher than 1 for both the fuel wood cooking stove and the charcoal cooking stove. Results from

Table 5
Benefit and cost analysis of the ICS

Item	Fuel wood stove	Charcoal stove
Fuel saving (US$/stove/year)	5.39	31.15
Cost saving (US$/stove/year)	1.89	1.89
Investment cost (US$/stove/year)	1.88	1.88
B/C ratio	3.87	17.58
Emission reduction (tonne of CO_2 equivalent /stove/year)	1.98	5.32
Emission reduction cost (US$/tonne of CO_2 equivalent/year)	0.95	0.35

sensitivity analysis show that the ICS is economically attractive for all scenarios. The B/C ratio ranges from 11.41 in scenario 3 to 46.68 in scenario 10.

5. The potential of biogas production from household's livestock and the corresponding emission reduction through the small biogas digester (SBD)

5.1. Data and assumption of the SBD

To estimate the potential of biogas production from household livestock in Thailand, the required data are number of households holding livestock, number of livestock, number of animals suitable to each size of digester, and animal waste per day suitable to each size of digester. The households holding livestock and number of livestock are taken from [14], while the number of animals and animal wastes per day suitable to each size of digester are taken from [4]. The forecasting of the potential of biogas production from household's livestock in the period 2002–2030 is shown in Table 6.

Due to the success of the SBD implementation in Thailand, this study assumes that the consumption of LPG in the SBD scenario is replaced by biogas with more progressive rates than in the BAU scenario as shown in Fig. 3. The projection of the replacement rate of LPG consumption in the BAU scenario during 2002–2010 is taken from [11,15] and the existing trend is used to project the replacement of LPG consumption in the period 2011–2030. Then data are added into the LEAP model and the LEAP model automatically calculates the energy consumption and the corresponding emissions.

In terms of economic criterion, the benefit/cost ratio (B/C ratio) and the net present value (NPV) are chosen as the criteria for the decision making in the SBD investment. The investment cost of the SBD is US$ 675, US$ 825, US$ 1222.5, US$ 2150, and US$ 4000 per unit for the SBD under the selected sizes of 12, 16, 30, 50, and 100 m^3, respectively [16]. It is necessary to validate the result that is often fluctuated by some economic parameters. Thus, the sensitivity analysis is exercised here. Since the SBD has a long lifetime of 15 years [17] and [18], the interest rate and the inflation rate affect the cost of the SBD. As a result, two economic parameters considered in this study are (i) the change of the interest rates, and (ii) the change of the inflation rates. In 2002, the interest rate was around 6.75% and the inflation rate was 4.2% [19]. In addition, the target on the inflation rate of the monetary policy of the Thai government ranges from 0 to 3.5% [20]. Consequently, it is assumed that the change of the inflation rate from the base year is separated into three rates: 0.3, 1.75, and 3.5%. The reason for this assumption is that the lowest inflation rate

Table 6
The forecasting of biogas production potential from household's livestock in period 2002–2030

Livestock	Biogas production potential in selected years (ktoe)						
	2002	2005	2010	2015	2020	2025	2030
Beef cattle	17.4	16.0	14.0	12.2	10.6	9.2	8.1
Dairy cattle	284.1	341.9	465.6	634.0	863.3	1175.6	1600.9
Buffalo	23.8	16.4	8.8	4.7	2.5	1.4	0.7
Pig	42.2	47.9	59.3	73.3	90.7	112.3	138.9
Poultry	30.1	33.5	40.1	48.0	57.4	68.7	82.3
Total	397.5	455.7	587.6	722.2	1024.6	1367.2	1830.8

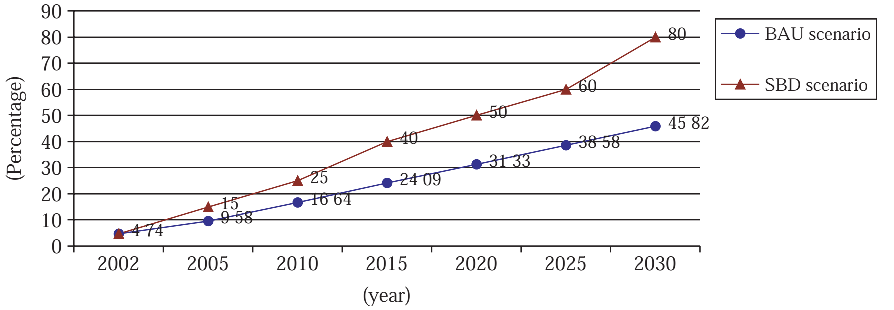

Fig. 3. The percentage of the replacement rate of LPG by biogas.

during the period 1997–2004 was 0.30% [21]. The 1.75% rate is the middle value of the target, and 3.50% rate is the highest value of the target. The assumptions of the change of the interest rate in the sensitivity analysis are (i) interest rate is decreased by 25 and 50%, and (ii) interest rate is increased by 25 and 50%. Therefore, twenty scenarios are set up for sensitivity analysis in this study (see Table 7).

5.2. The results of the SBD analysis from the LEAP model

Results show that total energy consumption in the residential sector in the BAU scenario is 7952.3 ktoe in 2002, increasing to 16,290.6 ktoe in 2030 as shown in Table 8. The difference between the SBD scenario and the BAU scenario is LPG and biogas consumption (see Table 9). In the SBD scenario, the LPG consumption in the residential sector could be decreased by 49.7 ktoe in 2005, and 511.3 ktoe. Similarly, the LPG could be decreased by 5780.9 ktoe during the study period. As a result, the country could also save from imported LPG around 16.9 million US$ in 2005, increasing to around 174.0 million US$ in 2030 or around 1967.2 million US$ during the study period at LPG price of US$ 340.3 per tonne of LPG in 2002 [22]. Even though it is assumed that LPG replacement by biogas in the SBD scenario is 2 times higher than the BAU scenario, biogas consumption in the SBD scenario in the base year is 37.1 ktoe, accounting for 9.34% of total biogas production potential and 1193.7 ktoe in 2030, accounting for 65.20% of total biogas production potential. This result points out that the potential to use biogas in place of

Table 7
Scenarios for the sensitivity analysis of the SBD

Scenario	Interest rate (% per year)	Inflation rate (% per year)	Scenario	Interest rate (% per year)	Inflation rate (% per year)
BAU	6.75	4.20	11	5.06	3.50
2	5.06	4.20	12	3.38	0.30
3	3.38	4.20	13	3.38	1.75
4	8.34	4.20	14	3.38	3.50
5	10.13	4.20	15	8.34	0.30
6	6.75	0.30	16	8.34	1.75
7	6.75	1.75	17	8.34	3.50
8	6.75	3.50	18	10.13	0.30
9	5.06	0.30	19	10.13	1.75
10	5.06	1.75	20	10.13	3.50

Table 8
Energy consumption in the residential sector in the BAU scenario

Fuel type	Energy consumption in selected years (ktoe)						
	2002	2005	2010	2015	2020	2025	2030
LPG	972.1	1085.1	1197.2	1267.5	1295.9	1306.8	1280.1
Kerosene	7.3	2.9	0	0	0	0	0
Electricity	1715.6	2184.2	3321.3	4957.1	6597.4	7916.4	8645.3
Fuel wood	2784.1	2925.2	3038.2	3096.0	3102.6	3160.7	3158.7
Charcoal	2391.2	2465.9	2501.4	2507.3	2486.1	2517.5	2510.9
Paddy husk	44.9	35.8	29.3	23.6	18.7	15.0	11.9
Biogas	37.1	87.5	176.1	284.0	400.1	538.9	683.7
Total	7952.3	8786.5	10,263.4	12,135.4	13,900.8	15,455.4	16,290.6

Table 9
Energy consumption in the residential sector in the SBD scenario

Fuel type	Energy consumption in selected years (ktoe)						
	2002	2005	2010	2015	2020	2025	2030
LPG	972.1	1035.4	1108.5	1079.5	1056.9	1006.9	768.8
Kerosene	7.3	2.9	0	0	0	0	0
Electricity	1715.6	2184.1	3321.3	4957.1	6597.4	7916.4	8645.3
Fuel wood	2784.1	2925.2	3038.2	3096.0	3102.6	3160.7	3158.7
Charcoal	2391.2	2465.9	2501.4	2507.3	2486.1	2517.5	2510.9
Paddy husk	44.9	35.8	29.3	23.6	18.7	15.0	11.9
Biogas	37.1	137.0	264.5	471.5	638.5	838.1	1193.7
Total	7952.3	8786.3	10,263.2	12,135.0	13,900.2	15,454.6	16,289.3

LPG is high. For example around 35% of total biogas production potential could be used instead of LPG in 2030.

Not only can Thailand reduce LPG consumption and expenditures from imported LPG, but it also can reduce the 16-20-0 fertilizer by using manure, a by-product from the SBD.

The quality of the manure is the same as the quality of the imported chemical fertilizer in the formula of 16-20-0 [4]. The potential of the manure production from the SBD is around 400 million tonnes per year or around 11,500 million tonnes during the study period. Thus, Thailand could reduce expenditures from the imported 16-20-0 fertilizer by around 50,000 million US$ per year or around 1,500,000 million US$ during the study period at the 16-20-0 fertilizer price of US$ 127.5 per tonne in 2001 [23]. Also, the farmers could earn around 5,000 million US$ per year from selling the manure or around 144,000 million US$ during the study period at the manure price of US$ 12.5 per tonne in 2002 [24]. Regarding the corresponding emissions, results from the LEAP model also show that corresponding emission mitigation in 2005 is 10 thousand tonnes of CO_2 equivalent and 140 thousand tonnes of CO_2 equivalent in 2030. The cumulative total corresponding emission mitigation is 1548.8 thousand tonnes during the planning period. These emission reductions are the result of using biogas instead of the LPG.

5.3. Results of the benefits/costs analysis

Results clearly show that the SBD is economically viable for all sizes of digester because the NPV is positive and the B/C ratio is greater than 1 for all scenarios (see Table 10). Even though the interest rate increases by 50% (from 6.75% to 10.13% per year) with the inflation rate of 0.3% per year in scenario 18.

Table 10
The net present value (NPV) and the benefit/cost (B/C) ratio of the SBD

Scenario	Biogas digester size (m^3)									
	12		16		30		50		100	
	NPV (US$/unit)	B/C	NPV (US$/unit)	B/C	NPV (US$/unit)	B/C	NPV (US$/unit)	B/C	NPV (US$/unit)	B/C
BAU	2233	1.58	4409	2.02	5752	1.71	11,811	2.03	29,240	2.59
2	2900	1.62	5624	2.08	7362	1.75	15,042	2.10	36,932	2.68
3	3837	1.67	7323	2.15	9617	1.80	19,564	2.16	47,675	2.77
4	1749	1.53	3524	1.95	4580	1.67	9455	1.97	23,624	2.50
5	1389	1.49	2867	1.89	3708	1.63	7704	1.91	19,444	2.42
6	1297	1.47	2697	1.87	3484	1.61	7252	1.89	18,365	2.39
7	1573	1.51	3204	1.93	4155	1.65	8601	1.95	21,587	2.46
8	2014	1.56	4009	1.99	5222	1.69	10,745	2.01	26,701	2.55
9	1625	1.52	3299	1.93	4281	1.66	8855	1.95	22,193	2.47
10	1996	1.55	3976	1.99	5178	1.69	10,657	2.01	26,490	2.55
11	2597	1.60	5071	2.05	6630	1.74	13,573	2.07	33,437	2.64
12	2066	1.56	4104	2.00	5348	1.70	10,999	2.02	27,306	2.56
13	5271	1.60	5026	2.05	6569	1.74	13,451	2.07	33,147	2.64
14	3408	1.65	6546	2.12	8586	1.78	17,497	2.13	42,767	2.73
15	1046	1.43	2237	1.81	2876	1.57	6029	1.84	15,443	2.31
16	1258	1.47	2625	1.86	3388	1.61	7059	1.89	17,906	2.38
17	1587	1.51	3228	1.93	4187	1.65	5078	1.78	21,744	2.46
18	852	1.39	1880	1.76	2403	1.53	5078	1.78	13,172	2.23
19	1016	1.42	2182	1.81	2802	1.57	5880	1.83	15,089	2.30
20	1268	1.47	2643	1.87	3413	1.61	7109	1.89	18,025	2.38

6. The potential of energy consumption and the corresponding emission reduction through the ICS and the SBD

According to sections 4 and 5, the potential reduction of energy consumption by the ICS and the SBD is 136.7 ktoe in 2005 and 1497.0 ktoe in 2030. The cumulative total energy consumption reduction during the study period is 22,887.7 ktoe. Corresponding emission also could be reduced by 60 thousand tonnes of CO_2 equivalent in 2005 and 710 thousand tonnes of CO_2 equivalent in 2030. The cumulative total corresponding emission mitigation during the study period is 11,589.8 thousand tonnes of CO_2 equivalent.

7. Identification and ranking of barriers to the adoption of the ICS and the SBD

One of the important keys to success in the implementation of high technology for the use of renewable energy (RE) in place of fossil fuel is how to overcome barriers to the adoption of the technologies. Despite the long history of research and development of renewable energy technologies (RETs), and the continuation of the implementation on RETs by the royal Thai government and many related agencies, the prospect of the RETs in Thailand still represents a small fraction of the primary energy supply. For instance, in 2001 the use of the ICS was only 0.17% of total stove usage in households [1] and [2]. Thus, in this section the barriers to the adoption of the ICS and the SBD are identified and prioritized by using the Analytic Hierarchy Process (AHP) model. In this study a practical AHP model is developed for the prioritization of the stakeholders, the criteria, and the barriers to the adoption of the ICS and the SBD technologies. It has four level structures as shown in Fig. 2. The objective of the AHP model in this study is to rank or prioritize the stakeholders, the criteria, and the barriers to the adoption of the ICS and the SBD technologies. Details of the stakeholders, the criteria, and the barriers are shown in Fig. 2.

The step after the arrangement of the AHP problem is the preparation of the questionnaire. The context in the questionnaire corresponding to each technology has three main sections. The first section is used to rank the stakeholders from the perspective of importance of stakeholders in the adoption of each technology. The second section is used to prioritize the criteria from the perspective of importance of criteria in the adoption of each technology. The third section is used to find out the priority values of each barrier by performing the pair-wise comparison between barriers under each technology. The AHP captures priorities from pair-wise comparison judgments of the elements of the decision with respect to the objective. Numerical values are assigned to the rating of each barrier. The values assigned are in the interval of 1–9. The numerical value of 1 is given for the same rating or equal importance of two considered barriers, while the value of 3 is assigned to the evidence that the rating of one barrier below another is of weak importance. On the other hand, the value of 9 is assigned to the evidence that the rating of one barrier over another is of highest importance. In addition, the numbers 2, 4, 6, 7, and 8 are used to facilitate compromise between slightly differing judgments.

7.1. Results and discussions of the priority values and ranking of stakeholders

Related to the AHP model, the pair-wise comparison of stakeholders with respect to the overall goal and to each other is performed. The priority values for stakeholders achieved from the pair-wise comparison corresponding to the ICS and the SBD technologies by

each stakeholder are presented. Consequently, the rankings of stakeholder in the adoption of each technology are obtained. In the ICS case, policy makers, experts, manufactures, and users have priority values of 0.41, 0.31, 0.17, and 0.11, respectively whereas in the SBD case the priority values are 0.52, 0.18, 0.19, and 0.11, respectively. Results show clearly that the policy maker is the most important stakeholder in the adoption of the ICS and the SBD technologies, while the least important stakeholder is the users. The results also imply that an excellent policy is the most important key in order to succeed in the implementation of the ICS and the SBD. The energy and environmental experts and the manufacturers do not affect the adoption of the selected technologies so much. This might result from the fact that the experts do everything following the policy to encourage both the manufacturers and the users. Regarding the manufacturers, their activities depend on demand. As a result, before implementing the project to the target group, the suitable policy must be considered first. The requirement of the users and the procedure to meet the users' requirement is the goal of the policy. Therefore, to get the appropriate policy, discussion among the related stakeholders is necessary. Consequently, the appropriate strategy is carried out.

7.2. *Results and discussions of the priority values and ranking of criteria*

The steps for the evaluation of priority values of criteria are the same as the stakeholders. The pair-wise comparisons of criteria are prepared. The priority values of criteria corresponding to the pair-wise comparison for each stakeholder are presented. The results point out that the financial criterion is the first considered criterion for all stakeholders in both ICS and SBD cases, with priority of 0.54 and 0.56, respectively. In the ICS case, the priority values of financial, government implementation, environmental effect, and technology criteria are 0.54, 0.22, 0.12, and 0.11, respectively whereas in the SBD case the priority values are 0.56, 0.18, 0.10, and 0.16, respectively.

7.3. *Results and discussions of the priority values and ranking of barriers*

The steps for the evaluation of priority values and ranking of barriers are the same as the ranking of stakeholders and criteria. The results of ranking of barriers are shown in Tables 11–12.

Table 11
The overall priority values of barriers corresponding to each stakeholder of the ICS

Barrier	Policy	Experts	Manufacturers	Users	Overall priority values	Rank
High cost	0.272	0.227	0.199	0.182	0.220	1
Lack of finances	0.166	0.186	0.135	0.128	0.154	3
Lack of information	0.118	0.157	0.151	0.275	0.175	2
Lack of experts	0.134	0.132	0.195	0.120	0.145	4
No consistent policy	0.083	0.093	0.061	0.102	0.085	6
Lack of reference	0.109	0.109	0.111	0.056	0.096	5
Lack of co-ordination	0.050	0.038	0.062	0.057	0.052	7
Inadequacy of R & D	0.035	0.017	0.048	0.033	0.033	9
Improper implementation	0.033	0.041	0.039	0.047	0.040	8

Table 12
The overall priority values of barriers corresponding to each stakeholder of the SBD

Barrier	Policy	Experts	Manufacturers	Users	Overall priority values	Rank
High cost	0.301	0.233	0.223	0.320	0.269	1
Lack of finances	0.284	0.171	0.128	0.094	0.169	2
Lack of information	0.126	0.162	0.124	0.147	0.140	4
Lack of experts	0.064	0.153	0.207	0.197	0.156	3
No consistent policy	0.091	0.107	0.060	0.059	0.079	6
Lack of reference	0.068	0.058	0.088	0.106	0.080	5
Lack of co-ordination	0.038	0.027	0.091	0.049	0.051	8
Inadequacy of R & D	0.029	0.088	0.079	0.026	0.056	7

The most significant barrier to the adoption of all selected technologies is the high investment cost. The three most important barriers to the adoption of the ICS are identified as (i) the high cost of investment, (ii) lack of information, and (iii) lack of source of finances. Regarding the SBD, the three most important barriers are (i) the high cost of investment, (ii) lack of financial source, and (iii) lack of experts and skilled manpower. These results suggest that to overcome the barrier to the adoption of the ICS and the SBD, the strategy to reduce the investment cost is the first consideration.

8. The strategy to succeed in the adoption of the ICS and the SBD technologies

As mentioned above, the ICS has been developed and implemented by the Thai government since 1984 [1], but the project still has failed. This situation implies that the present strategy is not suitable to resolve the problems. In addition, the results from the identification and the ranking clearly show that the policy maker is the most important stakeholder in the adoption of the ICS. The results imply that to succeed in the ICS implementation the proper policy is needed as the first priority. As a result, an alternative strategy is required to obtain proper policy in order to succeed in the ICS implementation. Thus, a new strategy of the ICS under the project 'the sustainable energy triangle strategy (SETS)' is implemented. At present the strategy to implement the ICS is to teach the stove producers and give them subsidy. Then the ICS is sold to the users with a little information on the benefits of using the ICS. Regarding the SBD, it is popular for the livestock farms to invest in for wastewater treatment. However, the problem of the SBD is the oversupply of biogas; therefore, the strategy to overcome this problem is also implemented.

8.1. The sustainable energy triangle strategy (SETS)

Unlike the present government's strategy, the SETS starts at the users who are the target group of the project. The SETS is designed by the Provincial Programme for Sustainable Energy (PRO-SE) of the Appropriate Technology Association [21] (see Fig. 4). The SETS is designed under the belief that the success of everything is based on the cooperation of concerned people and it will occur when the people understand how it affects them. By using the SETS, the process starts with telling and teaching the target groups about the effectiveness of the use of energy, and then training them to collect and investigate the energy used in their area. The result from this step is the energy situation of that area.

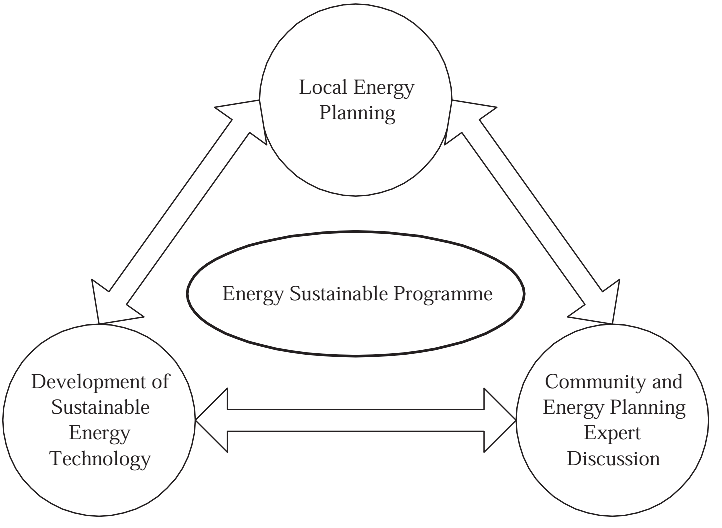

Fig. 4. Sustainable energy triangle strategy (SETS).

The next step is to help them understand about the data of energy used in their area; for example, how much they have to pay for the use of energy compared with the total revenue, how to reduce their energy consumption, and what is the benefit from the energy consumption reduction. Consequently, the energy planning for that area is obtained together with the strategies to reduce energy consumption which are designed by local people and one of those strategies is the ICS. Using the SETS, the implementation of the ICS and other technologies such as charcoal production with efficient process are successful.

The SETS was applied in 5 provinces in northeastern Thailand as the pilot project in 2002. They are Surin, Roi-Et, Khonkean, Ubolratchathani, and Nakornracchasima provinces. The results of the pilot project showed that the traditional cooking stove (TCS) was replaced by the ICS more than 20% within one year. For examples, at Dongkrungyai village in Roi-Et province about 22.9% of the TCS was replaced by the ICS in 2003. There are 1211 households in this area and all of them used the TCS for cooking. Based on the failure in the past of the ICS implementation, the project target was to replace the use of the TCS by 3% in 2003, accounting for 48 units of total TCS used. However, 364 unit of TCSs were replaced by the ICS in 2003, accounting for 22.9% of total TCS [25]. This result proves that SETS is the appropriate strategy to promote the use of the ICS. Moreover, the ICS producers in Dongkrungyai said that the TCS would be replaced by the ICS around 50% in total within 2005 [25]. On the other hand, they said that the current problem is the low production capacity of the ICS because the ICS is not only used in Dongkrungyai, but also in other areas such as Rayong, Cholburi, and Uttaradit provinces. The distribution of the use of the ICS is a result from people in Dongkrungyai buying the ICS for their relatives who live in other areas. The benefits of the use of the ICS then are described to other people. As a result, the ICS supply in Dongkrungyai is lower than the demand. It clearly shows that the proper strategy of the ICS implementation is the key role of the success to the adoption of the ICS.

8.2. The biogas pool project (BPP)

Due to the popularity of the biogas digester investment as the wastewater treatment system in the farms of Thailand, the present problem from some SBDs is the oversupply of biogas. To solve this problem, the oversupply of biogas is normally released to the atmosphere. This situation is very dangerous to the climate because about 50–70% of biogas is methane (CH_4) [26], one of the greenhouse gases. Hence, the proper direction to solve this problem is necessary. The best solution to this problem is to use biogas as much as possible and it is found that offering the oversupply of biogas to local people living on nearby farms for cooking is one of the alternative strategies. The same as other farms, at first the pig farm located at Sobsa village, Chiang Mai province in north of Thailand, invested in the biogas digester as the wastewater treatment system and as the tool to reduce the odour pollution [27]. As a result of oversupply of biogas and complaints by local people living nearby the farm, biogas was offered to the local people in 2000. Since 2000 this project has functioned without any technical problems. In 2002 it was found that all households in Sobsa village used biogas stove for cooking. Therefore, it is believed that this project is one of the alternative strategies to solve the problem of the oversupply of biogas, as well as the water and odour pollution; hereafter called 'Biogas Pool Project (BPP)'. To construct the BPP, the main biogas pipeline is connected to the digesters and then it is laid under the ground along the main street of the village. Then the sub-pipeline is connected to the main pipeline to deliver the biogas to households. The costs and benefits of the BPP in 2000 are as follows.

- The costs: (i) the construction cost of digester was US$ 8000, biogas pool project construction cost was US$ 420 (US$ 10 per household), (ii) gas stove cost was US$ 399 (US$ 9.50 per household), (iii) main tube cost was US$ 375, and (iv) sub-tube cost was around US$ 94.50 (US$ 2.25 per household).
- The benefits: (i) LPG saving per year (for households) the saving was around US$ 2948.40 (US$ 70.20 per household) at the LPG price of US$ 0.39 per kg [22] or around 7560 kg (180 kg per household) and for the farm, the saving was around US$ 386.66 or 991.43 kg, and (ii) revenue from selling manure per year was US$ 569.64. The manure market price in 2002 was US$ 0.20 per 30 kg [27].
- The total cost of the project is US$ 9288.50 per year while the total tangible benefit is US$ 3904.70 per year. As a result, the simple payback period of this project is around 2.38 years. Not only is LPG consumption reduced, but also fuel wood and charcoal consumption, because other types of stove were replaced by the biogas stove in all households in Sobsa village.

9. Discussions and conclusions

Though the ICS and the SBD technologies are important technologies for reduction of energy consumption and the corresponding emissions, the adoption of the ICS in Thailand was not success in the past, while the SBD faced the problem of oversupply of biogas. Results from the LEAP model reveal that the potential to reduce energy consumption and the emissions by both RETs is high. In the ICS case, total energy saving in the study period is 27,887.7 ktoe and total corresponding emission mitigation is 10,040 thousand tonnes of

CO_2 equivalent. In the SBD case, total energy saving in the study period is 5,780.9 ktoe and total corresponding emission mitigation is 1550 thousand tonnes of CO_2 equivalent. Also, both RETs are economically viable from the user's point of view. Results from the identification and the ranking of the adoption of both RETs show that the policy maker is the most important stakeholder to the adoption of both RETs and the financial is the first considered criterion for all stakeholders to invest in the ICS and the SBD. Regarding the barriers, results from AHP analysis show that the three most important barriers to the adoption of the ICS are identified as follows (i) the high cost of investment, (ii) lack of information, and (iii) lack of source of finances. Regarding the SBD, the three most important barriers are (i) the high cost of investment, (ii) lack of financial source, and (iii) lack of experts and skilled manpower. These results suggest that to overcome the barrier to the adoption of the RETs, the strategy to reduce the investment cost is the first consideration. As the most important stakeholder is the policy maker, it implies that the strategy to implement the ICS must be adapted. Therefore, the SETS strategy is presented as the appropriate strategy to implement the ICS. The results show that more than 20% of the TCS were replaced by the ICS within one year by using the SETS stratetgy. On the other hand, only 0.17% of the TCS was replaced by the ICS in 2001 by using the earlier strategy to implement the ICS. The SBD is popular to invest in for the farms as the wastewater treatment system. However, the oversupply of the biogas seems to be the difficult problem because the farmers normally release the biogas to the atmosphere. Hence the biogas pool project (BPP) is presented as the alternative strategy to resolve the problem. The results show that not only is the problem resolved, but also the consumption of fuel wood, charcoal, and LPG are reduced. Results also show that the BPP is economically feasible for Thailand.

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